MODELING THE EFFECT OF FROZEN GROUND ON SNOWMELT/RAINFALL-RUNOFF PROCESSES

V.I. Koren, Q.Y. Duan, and J.C. Schaake, Jr.
National Weather Service
Silver Spring, Maryland
Tel: 301-713-1018
Fax: 301-713-1051
email:vkoren@smtpgate.ssmc.noaa.gov

Introduction. Heat and moisture transfer processes in the aeration zone play an important role in the precipitation-runoff (P-R) relationship for river basins where seasonal soil freezing/thawing occurs. Seasonally frozen soil can significantly influence the amount of runoff generated during winter and spring. Lack of vegetation during winter, shallow snow cover, and cold temperature are ideal conditions for formation of deep frost. Such conditions are common in the upper Midwest of the United States and in northern Russia.

Considerable theoretical research has been done to study the physical processes of soil freezing/thawing at a point and over a small plot area (Dingman, 1975; Motovilov, 1977). However, most basin-scale P-R models have not considered the effect of frozen soil. Many P-R models do consider the effect of snowfall by including additional equations representing the snow accumulation/melting processes. But this is done without substantial changes in the equations describing the runoff formation processes. This approach may not be effective in representing either the snow accumulation/melting or the snowmelt/rainfall-runoff (S/R-R) processes in cold regions because the water-absorbing properties of the soil in these regions vary considerably in response to soil freezing/thawing. Conceptual approaches to accounting for the effect of frozen ground on runoff were proposed in the Hydrometeorological Center Model of Russia by Koren (1980), and in the Sacramento Soil Moisture Accounting Model by Anderson and Neuman (1984). These simple approaches showed promise in improving runoff simulation in the cold regions of the United States and Russia during winter and spring.

This paper presents a methodology to model the effect of frozen ground on S/R-R processes by using a limited number of variables to account for energy exchange in the aeration zone. Although the frozen ground model could be coupled with any commonly available P-R models, most of the results and analyses presented here were obtained on a Simple Water Balance (SWB) model developed by Schaake et al. (1995).

Frozen ground model. A distinguishing feature of the S/R-R processes in lowland basins is the possible formation of a practically impermeable layer in the frozen soil. Some critical conditions of water/heat storage in soil have to exist to create this layer. Laboratory experiments showed that, depending on soil moisture content and other physical soil characteristics, an impermeable layer can be formed only if the soil temperature is below some critical value (Komarov, 1957). These experiments also established some empirical relationships between the depth of frozen soil and soil temperature.

Some field experiments showed that the extent of the impermeable layer in a basin is related to the product of basin average frozen depth, Z, and soil moisture content, w. Here we assume that in a particular basin there exists a certain critical value of the product, $U_c=Zw$, above which soil is practically impermeable. We also assume that Z and w are independent random variables with probability density functions $f(Z)$ and $f(w)$. Under these assumptions, the fraction of the area on which the impermeable layer is formed is:

$$F_c = 1 - \int_0^\infty \int_0^{U_c/w} f(Z) f(w)\, dZ\, dw \tag{1}$$

There are very limited data available to obtain the probability density functions of frozen depth and soil moisture content. Analysis of the measurements for a few basins in the European part of Russian showed that, in general, $f(Z)$ and $f(w)$ can be approximated by Gamma distribution. A practical equation for computing F_c was obtained by assuming that soil moisture distribution is uniform and that the distribution of frozen depth is defined as a Gamma distribution with its parameter rounded to the integer value (Koren, 1980). i.e.,

$$F_c = \exp\left(-\frac{\alpha_Z U_c}{Zw}\right) \sum_{i=1}^{\alpha_Z} \frac{\left(\frac{\alpha_Z U_c}{Zw}\right)^{\alpha_Z - i}}{\Gamma(\alpha_Z - i + 1)} \tag{2}$$

where α_Z is a parameter in the distribution function of frozen depth.

The equation for calculating the areal average frozen/thawed depth was obtained from a heat transfer equation on the assumption that there is no heat transfer across the lower boundary of the soil layer. The temperature distribution in the frozen layer and in the snow cover is linear. At sub-zero temperature all soil moisture is in a solid state. Conversely at positive temperature, soil moisture is in a liquid state. Water percolating during thawing does not participate in heat-transfer processes. i.e.,

$$Z_{t+dt} = -\frac{\lambda H}{\lambda_s} + \sqrt{\left(\frac{\lambda H}{\lambda_s} + Z_t\right)^2 + \frac{2\lambda |T| dt}{Lw}} \tag{3}$$

where H and T are the snow depth and surface temperature averaged over the time interval dt, L is the latent heat of ice fusion, λ is the thermal conductivity of the frozen/thawed soil, λ_s is the thermal conductivity of snow. Snow depth and density were calculated by taking into account snow compaction.

Coupling with water balance and snowmelt models. The frozen ground model was coupled with the Simple Water Balance (SWB) model (Schaake, et al., 1995). The SWB model is essentially a conceptual model controlled by five parameters. The spatial variability of the main variables is accounted for by probability averaging. The space scale can be a pixel in the remote sensing array, a small catchment, a river basin or a GCM grid cell.

Consider a column of the land surface as a two-layer system with a rather thin upper layer and a deeper lower layer. The upper layer is a short-term retention storage that is used mainly to represent the capacity of the vegetation canopy to hold water. It also represents the capacity of the soil surface to store water in small depressions and/or in the first few millimeters of soil surface. Inflow to this upper layer is precipitation. All inflow will be retained until the water storage capacity is filled. The excess inflow, P_x, becomes input into the lower layer. Water evaporates from the upper layer at the rate of potential evaporation. The lower layer is the main soil moisture storage reservoir. Its capacity depends mostly on the rooting depth and soil porosity. Both surface and subsurface runoff and evapotranspiration are outflows from this layer. Evapotranspiration from the lower layer takes place only when there is not enough water to evaporate from the upper layer. The actual evapotranspiration in the lower layer depends on soil moisture content of the lower layer and the spatial variation pattern of maximum soil moisture holding capacity in the upper layer. An exponential distribution is used to account for the spatial variation of the maximum soil moisture holding capacity in the upper layer. The actual evapotranspiration in the lower zone is less than or equal to the residual potential evapotranspiration after the upper layer evapotranspiration is met.

Subsurface runoff is assumed to be a linear function of the lower layer moisture content in excess of a minimum threshold. The surface runoff equation is obtained as the spatial average of the probability distribution of point values. It is assumed that surface runoff at any point is controlled by a runoff excess mechanism. In the coupled version of the frozen-ground/SWB model, the portion of the basin with an impermeable layer produces direct surface runoff. Therefore, the total surface runoff is computed by:

$$Q_s^* = Q_s(1-F_c) + P_x F_c \tag{4}$$

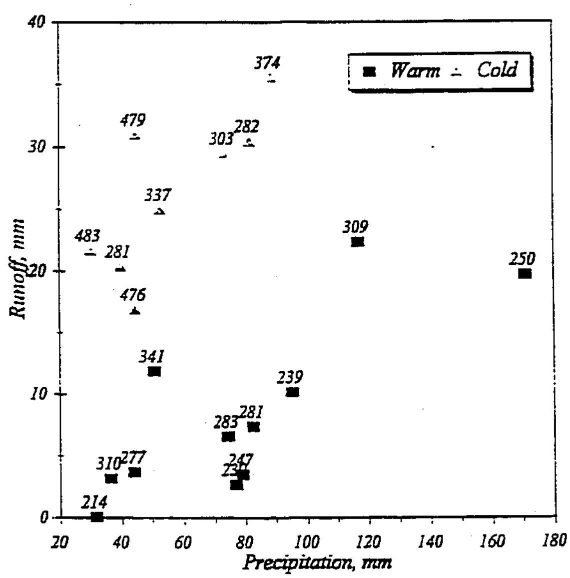

Figure 1. Precipitation-runoff relationship for flood events during warm and cold seasons. Soil moisture in mm is at the points

where where Q_s is surface runoff calculated without frozen ground.

A snow accumulation and ablation model of the National Weather Service developed by Anderson (1976) was used to account for snowmelt processes. During rain-on-snow periods the model uses the energy balance snowmelt equation. During non-rain periods snowmelt is calculated using the seasonally varied melting factor. Snow density is calculated using the approximate solution of the Anderson-Yosida's equation, which accounts for the effect of the snow compaction (Anderson, 1976).

Results and Discussion. The model was tested on the Root River basin at Lanesboro (1593 km^2), located in Minnesota. The basin is generally flat to rolling, and predominately agricultural.

Six hourly precipitation and temperature, and daily potential evaporation and discharge data were collected for water years 1964 through 1972. The mean monthly temperature varies from 21 °C in July to -12 °C in January. During some winters snow accumulated early, insulating the ground. During other years the ground froze to depth of up to 2 m before any substantial snow accumulation developed. Thus, the freezing processes are very important for runoff formation in this basin. Figure 1 displays differences of the runoff coefficients for cold- and warm-season flood events. Using only the soil moisture content can not explain the significant differences in the amount of runoff generated by precipitation events of similar size.

The following numerical experiments were conducted. First the SWB model was calibrated without the frozen ground component. The model performance was very poor. Winter time floods were usually underestimated. Summer time floods, on the other hand, were overestimated. The second test was to recalibrate the SWB model with the frozen ground component incorporated. The critical value of the ice content, U_{σ} was calibrated along with the five water balance model parameters. Inclusion of the frozen ground model significantly improved the results. The mean root square errors of daily observed and simulated streamflow values were reduced from 16.8 cms to 10.2 cms.

Figure 2 shows the monthly averaged water balance components both with and without the frozen ground model. It is clear from this figure that, without considering the frozen ground, runoff was underestimated significantly, while soil moisture content was overestimated during spring and early summer. As a result the actual evaporation is overestimated for that period.

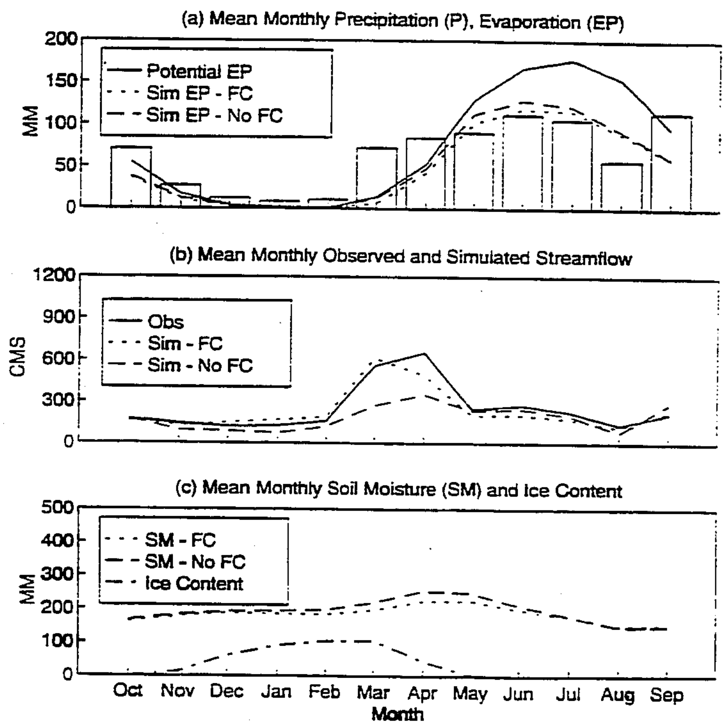

Figure 2. Comparison of observed and simulated monthly time series. (FC - frozen ground component included; No FC - otherwise)

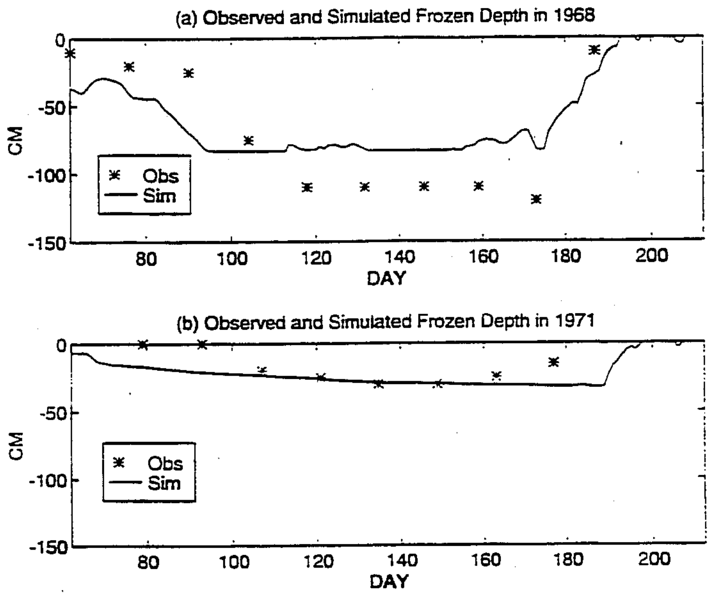

Figure 3 Observed and simulated frozen depth near the Root River

An example of observed and simulated frozen and snow depths is presented in Figure 3. The observed data were obtained from general frost-depth maps for Wisconsin. Considering that the Root River is about 100 km from the Wisconsin border, the match between the observed and simulated frozen depths is quite reasonable.

Summary. The results indicate that the inclusion of a frozen ground component in S/R-R models can significantly improve the runoff simulation. Without considering frozen ground, runoff would be underestimated substantially, while evaporation fluxes and soil moisture storage would be overestimated during spring-summer season. This study takes a simplistic conceptual approach to model the frozen ground. Only conventional hydrologic data and temperature data were used. To evaluate the frozen ground model more comprehensively, measurements of snow cover, frozen depth and soil temperature profile will be needed.

References

Anderson, E.A., 1976, A Point Energy and Mass Balance Model of a Snow Cover, NOAA Technical Report NWS 19, U.S. Dept. of Commerce, Silver Spring, Maryland, 150pp.

Anderson, E.A., and P.J. Neuman, 1984, Inclusion of frozen ground effects in a flood forecasting model, The 5th North. Res. Basins Symp. and Workshop, March 19-23, Vierumaki, Finland, 14p.

Dingman,S.L., 1975, Hydrologic Effects of Frozen Ground, Special Report 218, Cold Regions Research and Engineering Lab, Hanover, New Hampshire, 55p

Komarov, V.D., 1957, Laboratory experiments on the frozen soil infiltration, Proceedings of the CIP, Gidrometeoizdat, Moscow, USSR (in Russian)

Koren, V. I., 1980, Modeling of processes of river runoff formation in the forest zone of the European USSR, Soviet Met. and Hydrol., Allerton Press, Inc., 10, New York, 78-85.

Motovilov, J. G., 1977, Mathematical model of water infiltration into frozen ground, Proc. of Hydromet. of the USSR, vol. 191, 18-28, (in Russian).

Schaake, J.C., V. I. Koren, and Q.Y. Duan, 1995, A simple water balance (SWB) model for different spatial and temporal scales: 1. Model formulation, J. Geophy. Res., in press.

INTERNATIONAL GEWEX WORKSHOP

on

COLD-SEASON/REGION HYDROMETEOROLOGY

Summary Report and Proceedings
Banff, Alberta, Canada
22-26 May 1995

compiled by

Terry W. Krauss

and

Thomas R. Carroll

from

Contributions of Workshop Participants

September 1995

IGPO Publication Series
No. 15